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# FPGA Based Time Domain Passivity Observer and Passivity Controller

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***Abstract*— In this paper, Field Programmable Gate Array (FPGA) based time domain Passivity Observer and Passivity Controller is proposed to improve the stability range of haptic interfaces. A simplified PO/PC algorithm is implemented on FPGA for improving the control efficiency. Thanks to the fast sampling rate and the parallel processing ability of the FPGA, the PO/PC can be updated irregularly only when encoder pulse happen instead of updating every single msec. Reference current calculated from virtual wall was used for the energy calculation instead of measured motor current to avoid signal noise. The simplified FPGA based PO/PC approach is compared with the software based approach. The experimental results show that the noise behavior during low velocity contact is dramatically reduced.**

## I. INTRODUCTION

Haptic interfaces are closed loop sampled-data systems which consist of human operator, haptic device, and virtual environment. The existence of sampling and latency phenomena in the system can generate energy and may lead to instability if the generated energy cannot be dissipated. Moreover, the sustained or growing oscillations induced by unstable behavior can damage hardware, distort the perception of the virtual environment, or even worse, inflict physical harm to the operator. Therefore, it has been a critical issue to increase the stability range of haptic interfaces.

A lot of research has been done to increase the stability range of haptic interfaces. One approach is the software based approach utilizing simulated virtual damping. Colgate et al [1] proposed the "Virtual Coupling" scheme to ensure system passivity by building a spring-damper connection between the virtual environment and the haptic display. Adams and Hannaford [2] generalized and extended the concept by deriving optimal virtual coupling parameters using a dynamic model of a haptic device. Hannaford and Ryu [3] proposed a time domain Passivity Observer (PO) and Passivity Controller (PC) approach to preserve system passivity by injecting variable virtual damping. The PO was designed to monitor the system passivity state by integrating the produced energy in time domain while the PC was used to dissipate the amount of generated energy. The PO/PC was implemented by real-time based software. Lee and Spong [4] proposed a passivity based simple PD control scheme with damping compensation for constant time delay. Kim and Ryu [5] proposed a passivity based energy bounding algorithm. It restricts the amount of generated energy from the sample and hold within a consumable energy limit. However, for improving the stability range, the software based approach has its fundamental limitation on virtual damping.

An alternative approach is adding physical damping instead of virtual damping. Colgate and Brown [6] found that physical damping is essential to ensure stability. They [6] demonstrated experiments with viscous damper by attaching it to motor shaft. It significantly increased the stability range. However, the added physical damping results in the haptic interface feeling highly viscous when working in free space. It also increased the mechanical complexity. Mehling and Colgate [7] developed electrical damping with an electrical circuit, which can change the damping parameter. Recently, an active electrical damping method was presented by Weir and Colgate [8]. They added programmable electrical damping to haptic interfaces using analog electronics in the motor amplifier. Gosline and Hayward [9] proposed eddy current brakes (ECBs) to provide tunable physical damping based on time domain passivity approach.

Recently, Field Programmable Gate Array (FPGA) has been used for improving the control performance of haptic interfaces. Ishii [10] improved the performance of the bilateral teleoperation based on disturbance observer. Kopp [11] expanded the passivity range of virtual stiffness by reducing the sampling period with FPGA. Vasudevan et al. [12] increased the stiffness range of virtual wall by implementing the haptic control loop on FPGA. However, it sacrificed the rendering complexity. When the virtual environment gets complex, it becomes difficult to implement with FPGA.

In [13], FPGA based hardware implementation of the time-domain passivity controller was introduced to solve several issues on software based damping injection. The noise behavior of the conventional software based time-domain passivity controller was significantly removed through this hardware implementation. The FPGA based PO/PC method separates the virtual environment rendering and the stability issue. In this paper, we simplify the hardware implementation of the PO/PC algorithm to improve the control efficiency. Instead of updating the PO/PC every sampling time, it is updated irregularly only when encoder pulse happen. Thanks to the fast sampling rate and parallel processing of FPGA, it is possible to capture every single encoder pulse while running separate control loops simultaneously. In [13], we used measured motor current to estimate more accurate energy flow. But there was some drawback like measured

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noisy signal can make the energy more fluctuating and degrade the control performance. In this paper, we get back to use reference current for energy calculation. The FPGA based PO/PC scheme is compared with the conventional software based PO/PC. Experimental results demonstrate the improved performance.

## II. REVIEW OF THE TIME DOMAIN PASSIVITY APPROACH

In this section, the time-domain passivity control approach is reviewed. The sign convention for all forces and velocities is defined so that their product is positive if power enters the system. The following is a widely known definition of passivity.

Definition: A one-port network with initial energy storage is passive if and only if

$$\int_0^t f(\tau)v(\tau)d\tau + E(0) \geq 0, \forall t \geq 0 \tag{1}$$

where $f$ is force, $v$ is velocity. Equation (1) states that the energy supplied to a passive network must be greater than negative $E(0)$ for all time [16], [17].

In haptic interfaces, the force and velocity can be measured as discrete values by the computer and (1) can be calculated in real time by appropriate software. This software is very simple in principle because at each time step, (1) can be evaluated with few mathematical operations.

The conjugate variables that define power flowing in such a system are discrete-time values, and the analysis is confined to systems having a sampling rate substantially faster than the dynamics of the system. We can easily "instrument" one or more blocks in the system with the following "Passivity Observer" (PO) to check the passivity:

$$E_{obsv}(n) = \sum_{k=0}^{n} f(k)\Delta X(k) \tag{2}$$

where $\Delta X(k)$ is the displacement during one sampling time.

If $E_{obsv}(n) \geq 0$ for every $n$, this means the system dissipates energy. If there is an instance that $E_{obsv}(n) < 0$, this means the system generates energy and the amount of generated energy is $-E_{obsv}(n)$.

Consider a one-port system which may be active. Depending on operating conditions and the specifics of the one-port element's dynamics, the PO may or may not be negative at a particular time. However, if it is negative at anytime, we know that the one-port may then be contributing to instability. Moreover, since we know the exact amount of the generated energy, we can design a time-varying damping element to dissipate only the required amount of energy. We call this element a "Passivity Controller" (PC). The PC takes the form of a dissipative element in a series or parallel configuration depending on the input causality [3]. Fig. 1 shows the series configuration of the PC for a one-port network system. $\alpha$ is an adjustable damping elements at the

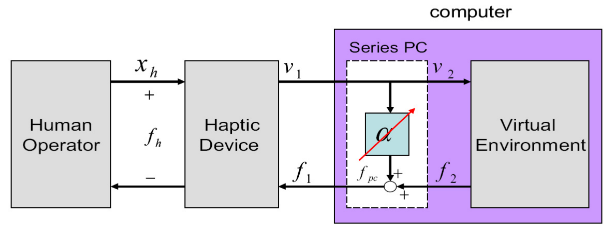


Fig. 1. Conventional PO/PC for one-port network with impedance causality

port which was realized inside computer by some real-time software.

Even though the PO/PC has been successfully applied to many different haptic interfaces, one of the problems was the noise behavior during low velocity contact. To remove the noise behavior, reference energy following and new algorithm which ignore the produced energy near zero velocity has been proposed [19]. In our previous research [13], FPGA was tested to solve several issues on software based damping injection method including the noise behavior.

## III. FPGA-BASED PASSIVITY OBSERVER AND PASSIVITY CONTROLLER

FPGA is a device that contains a matrix of reconfigurable gate array logic circuitry. The main feature of FPGA is parallel processing. While a conventional PC can only execute one program at a time, FPGA can execute multiple tasks at different rates simultaneously. Furthermore, FPGA can operate many orders of magnitude faster than microprocessor based control systems. Additionally, FPGA use dedicated hardware for processing without requiring any operating system, which provides the highest level of reliability. For the advantages above, FPGA offers advantages of implementing haptic controller with high sampling rate in real-time.

The main objective of the FPGA based PO/PC scheme is to remove the noise behavior of the software implemented PO/PC. We expect the stability issue could be separated from virtual environment design by implementing the time domain Passivity Observer and Passivity Controller on FPGA based motor driver, which means that the haptic controller can be designed without considering the stability and complexity of virtual objects.

Fig. 2 shows the block diagram of the FPGA based motor controller in where the PO/PC is implemented. This controller is structured as a set of functional modules. Encoder is connected to the counter module which detects the signal states and pulse events. Those events are inputs of the PO/PC module which communicate with host computer where virtual environment is rendered. The PO/PC is updated only when pulse events happen. The output from the PO/PC module is reference current and it is transfered to the current control module which produces PWM signal. The current acquisition module is optional which depends on the application. In the current design, this module was not used. The biggest advantage of FPGA is that each of these modules operates in parallel.

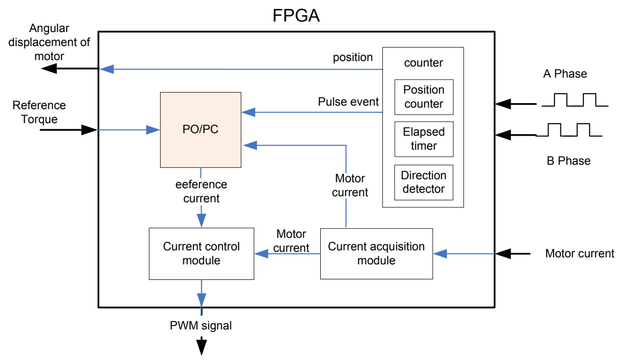


Fig. 2. Block diagram of FPGA-based PO/PC system

TABLE I

DETECTION LOGIC

| A | B | Position counter | Direction |
|---|---|---|---|
| ↑ | L | +1 | forward |
| ↑ | H | -1 | backward |
| H | ↑ | +1 | forward |
| L | ↑ | -1 | backward |
| ↓ | H | +1 | forward |
| ↓ | L | -1 | backward |
| L | ↓ | +1 | forward |
| H | ↓ | -1 | backward |

## A. Counter Module

The function of the counter module is to acquire the position displacement by detecting the encoder pulses and measure the time duration between two successive encoder pulses. In contrast to adding extra counter board, the counter can be easily realized on FPGA without any hardware limitation. Fig. 3 shows the block diagram of the encoder counter. It consists of comparator, logic detector, position counter, elapsed time counter and direction detector. The comparator compares the current value and the previous value of encoder signals to detect the change of the state. There are two states and two edges of the signals, high level, low level, rising edge, and falling edge. The detection logic to get the current position and direction is shown in table I. The elapsed time is measured between each successive pulses which can be used in velocity calculation [13]. In this PO/PC application, the elapsed time counter is masked since it is not necessary in the simplified scheme. The update rate of the counter module is 40MHz.

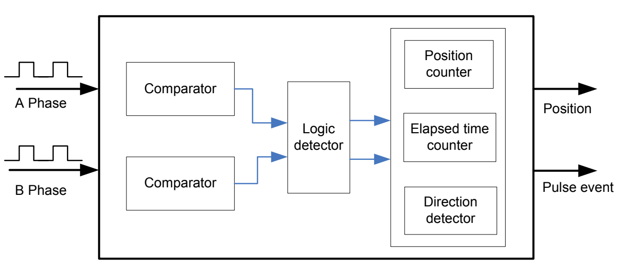


Fig. 3. Block diagram of encoder counter

## B. PO/PC module

Fig. 4 shows the flow chart of the PO/PC algorithm, and how it was implemented inside FPGA. Virtual wall is independently rendered on host computer with an update rate of 1KHz. When collision is detected, a reference force is sent to the FPGA from the host. The PO/PC module is updated irregularly only when the encoder pulse is detected by the counter module. The reference current was used for energy calculation instead of measured motor current [13] to avoid the measured signal noise.

1) Compute the reference current, where $f_e$ is the reference torque and $k_t$ is the motor torque constant.

$$i_{ref} = f_e/k_t \tag{3}$$

2) Update the Passivity Observer value if pulse event happen. Reset the PO value to zero if the collision is not detected.

$$PO += i_{ref} \tag{4}$$

Equation (4) is derived from (2). Based on equation (3), equation (2) can be renewed in the following form

$$PO += k_t i_{ref} \Delta X \qquad (Npulse) \tag{5}$$

The dimension of PO is $Npulse$. Since the PO is updated only when the pulse event happen, the position displacement $\Delta X$ is a constant value which is one pulse. Then, the equation (5) can be rewritten as

$$PO += k_t i_{ref} \qquad (Npulse) \tag{6}$$

Since $k_t$ is a constant value and will be canceled out by division later, the energy calculation can be simplified as (4) for simple realization.

3) Determine whether energy is produced or dissipated (i.e. whether the PO is positive or negative).
   - If the PO is positive, no modification on the reference current.
   - If the PO is negative, compute the value of the Passivity Controller

$$i_{pc} = -PO \tag{7}$$

then update the value of PO for next time step,

$$PO += i_{pc} \tag{8}$$

4) Apply the Passivity Controller to modify the reference current of the current control module.

$$i_m = i_{ref} + i_{pc} \tag{9}$$

5) Give reference current to current control module.

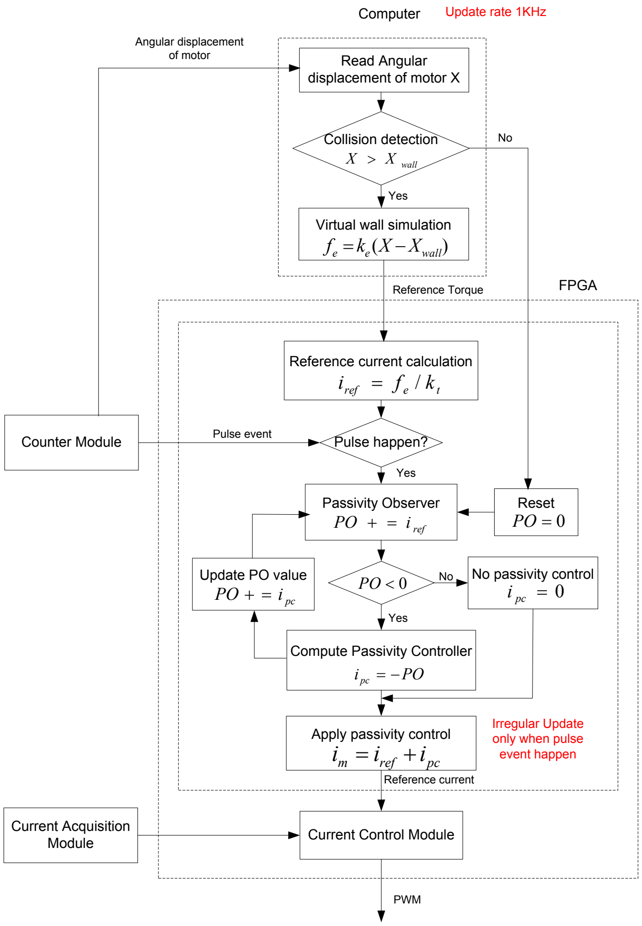


Fig. 4. Flow chart of PO/PC algorithm

## C. Current control module

The current control module is interfaced with the current acquisition module. It consists of current controller and PWM generator which produces PWM signal to drive the motor. The update rate of this module is controllable. In this case, it was set as 200 KHz. The current protection is included to avoid over-current. In the experiments, the maximum allowable current was set to 1.6A.

## IV. EXPERIMENTAL RESULTS

Experiments are conducted to show the performance improvement of the simplified hardware implementation of the time-domain Passivity Controller. The most sophisticated version of the software based PO/PC with reference energy and noise removal scheme [19] is compared to the proposed FPGA based scheme with the simplest version of PO/PC.

Fig. 5 shows the experimental setup with one-DOF haptic device. A brushed DC motor with MR encoder (1024PPR) is used for the one-DOF haptic device. Cable driven mechanism was used to magnify the motor torque 10 times. A Hall-effect current sensor with 185 $mV/A$ output sensitivity is included for measuring motor current. National Instrument PXI-7833R FPGA board was used to implemented the whole proposed PO/PC algorithm, and virtual environment is rendered inside computer on Windows XP with updating rate of 1 $kHz$. A virtual wall is located at $X_{wall} = -5.4\ mm$ with stiffness of 550 $N/m$. Fig. 6 shows Human operator pushes the one-DOF haptic device to make a contact with the virtual wall.

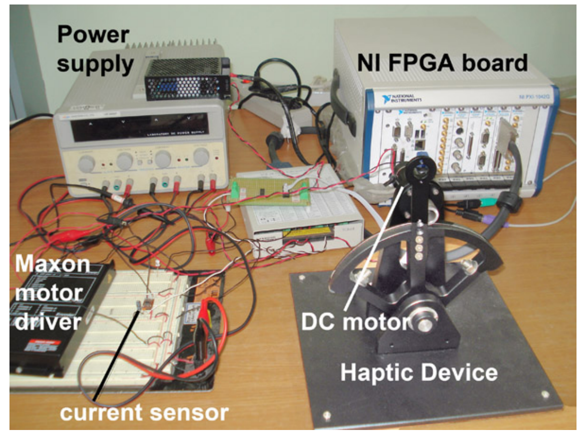


Fig. 5. Experimental setup

Fig.7 shows the case when the PC was not activated. The experiment was conducted on the FPGA with the simplified PO/PC algorithm discussed in section III. Position and force response was highly unstable while the operator was interacting with the virtual wall, and certain amount of active energy was produced at each contact.

Fig.8 shows the contact response with the software based PO/PC. The experiment was conducted with the lasted version of the software based PO/PC, where reference energy following method was included and the produced energy near zero velocity was ignored [19]. Velocity used in this algorithm was obtained by counting encoder pulses over a sampling period.

Even though the contact was stable in terms of the position response, after some time the PC started vibrating and the PO value kept falling down to a negative value. Human operator felt continuous vibration and the fidelity of the virtual environment rendering was lowered. This is because of the noise velocity signal during low velocity contact, and


Fig. 6. Human operator pushes the device to contact with the virtual wall

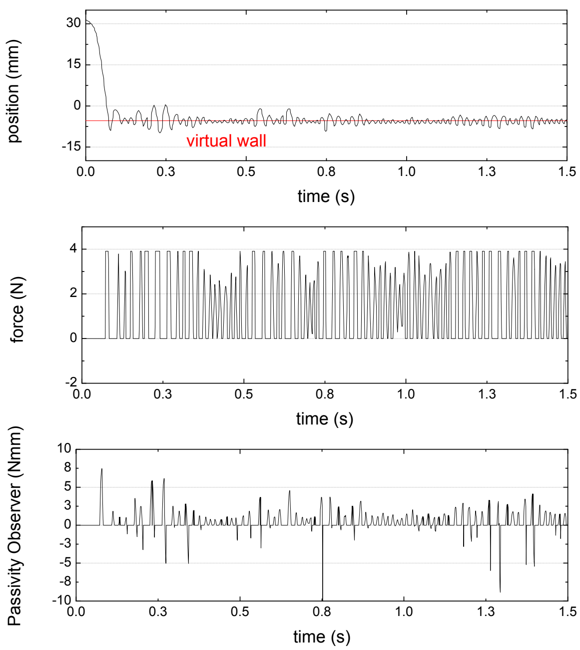


Fig. 7. Experimental results for the case when PC was not activated. Interaction was unstable

the fact that the PC was turned on and off too often. Note that the Passivity Controller force was bounded.

Fig.9 shows the contact response with the proposed FPGA based PO/PC method. Thanks to FPGA we can reduce the reaction time and remove the unnecessary operation. The noise behavior during the low velocity contact was dramatically reduced. Stable contact was achieved within several bounces and operator felt smooth interaction force.

## V. CONCLUSIONS AND FUTURE WORKS

This paper proposed a simplified version of FPGA based time domain PO/PC for improving the stability range of haptic interfaces and mainly remove the noise behavior of the software based PO/PC during low velocity contact. Thanks to the fast and parallel processing ability of the FPGA, the PO/PC algorithm can be simplified as having minimum number of the PC action. One of the advantages of this approach is that the controller for guaranteeing stability can be designed separately without considering the complexity of the virtual environment. In the near future, we plan to develop one board motor driver with the PO/PC embedded FPGA, which allow us to simply replace the conventional motor driver of haptic devices.

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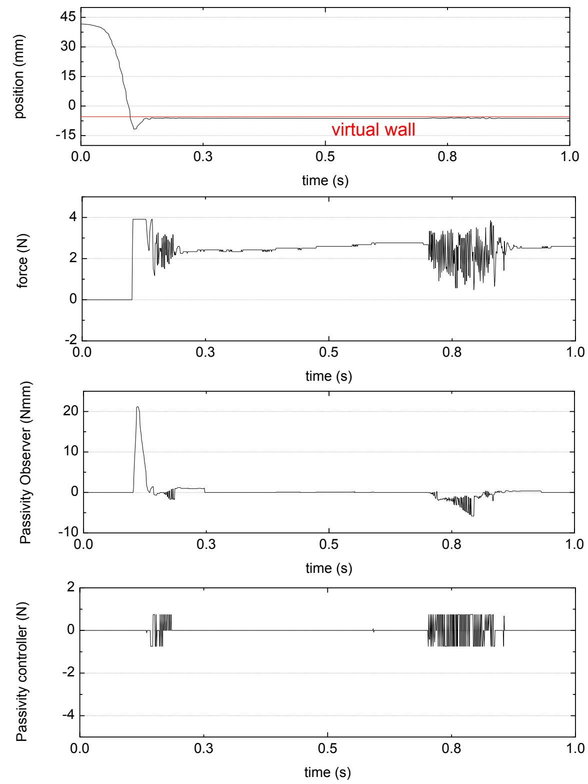


Fig. 8. Experimental results for the case when the conventional software based PC is turned on. Interaction was stable, but characterized by noise behavior.

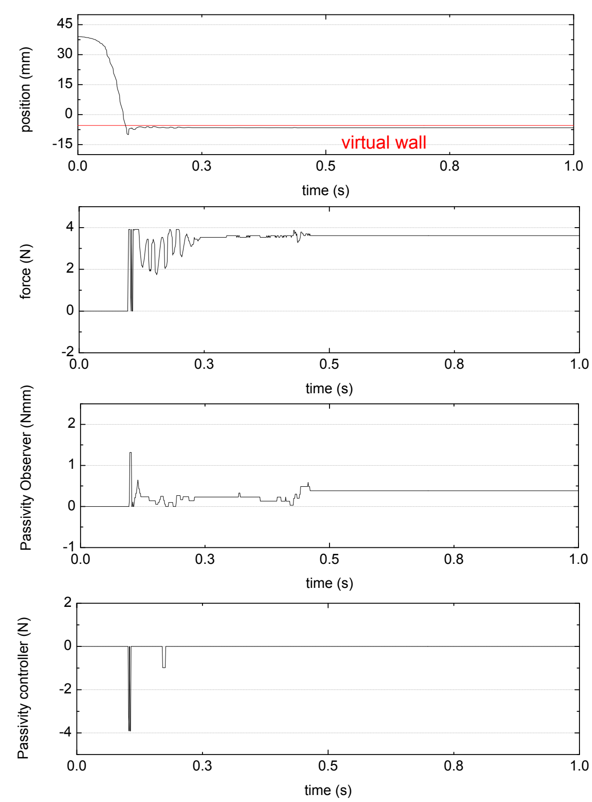


Fig. 9. Experimental results for the case when the FPGA based PC was activated. Interaction was stable, noise behavior was removed.

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